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# Pilot Study of Fluoride and Arsenic Removal from Potable Water

Aluminum Co. of America
Alcoa Center, PA

Prepared for

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Cincinnati, OH

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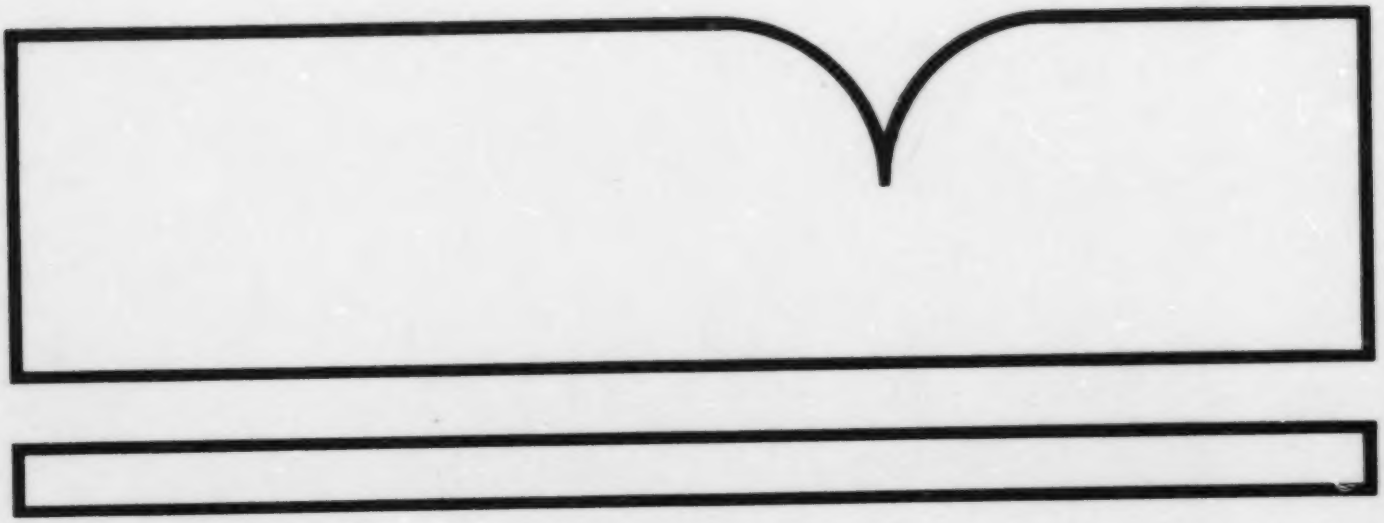

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16. ABSTRACT

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A schematic of a full-sized treatment plant is included, along with engineering estimates of operating and capital equipment costs for small communities. Operating costs are approximately 5¢/kL of treated water. (19¢/1000 gal.)

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# PILOT STUDY OF FLUORIDE AND ARSENIC REMOVAL FROM POTABLE WATER

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## FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

Fluoride and arsenic are two contaminants frequently found in high concentrations in drinking water. Activated alumina treatment will remove both elements from water, but the operating procedures vary slightly for each contaminant. Occasionally, the two contaminants are found together in the same water supply that presents a unique treatment problem. This report describes the results of two series of pilot plant tests to determine the optimum system for removing the two contaminants in combination in a ground water by activated alumina treatment. Construction and operating costs for small systems are also presented.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

## ABSTRACT

Pilot plant studies were conducted on the removal of fluoride and arsenic from potable water using activated alumina as the adsorbent. The tests were run using water from the community of Why, Arizona, that contained 3 mg/L fluoride and 0.15 mg/L arsenic.

The experimental data show that activated alumina is an effective means of treating this water. Major facts shown by the data are that: (a) arsenic is preferentially adsorbed on the activated alumina, (b) a stronger sodium hydroxide solution (4%) is required during regeneration of the activated alumina for arsenic than is required for fluoride (1%), and (c) the capacity of the alumina for removing fluoride is decreased by any arsenic remaining in the alumina. The pilot studies indicate that the preferred method of treating water with these combined contaminants is the use of two activated alumina columns in series.

A schematic of a full-sized treatment plant is included, along with engineering estimates of operating and capital equipment costs for small communities. Operating costs are approximately 5¢/kL of treated water. (19¢/1000 gal.)



This report was submitted in fulfillment of Contract No. 68-03-1351 by the Aluminum Company of America under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period 6/78 to 4/79, and work was completed as of 8/79.

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# SECTION 1

## INTRODUCTION

As of June 24, 1977, communities throughout the United States are required to comply with the U.S. Environmental Protection Agency (EPA) National Interim Primary Drinking Water Regulations, dated December 24, 1975.[1] Maximum contaminant levels in potable water supplies have been established for 10 inorganic chemicals, including fluoride and arsenic. The maximum contaminant level for fluoride varies from 1.4 to 2.4 mg/L, depending on the annual average of the maximum daily air temperatures. The maximum contaminant level for arsenic is 0.05 mg/L.

Techniques for the successful removal of excess fluoride from potable water sources with activated alumina have been developed by Rubel and Hager, Inc., Tucson, Arizona, and have been used in three full-scale operating plants. The first plant, in Desert Center, California, has been in operation since 1970. The second plant, at X-9 Ranch near Tucson, Arizona, has been in operation since 1972; and the third plant, in Gila Bend, Arizona, has been operating since 1978. These plants have been removing fluoride at operating costs of 2.5 to 4.0¢/kL (10-15¢/1,000 gal) of treated water for fluoride waters containing 4.5 to 7.5 mg/L fluoride. Further details on the operating techniques used in these plants are decribed in a 1978 EPA technical report[2] and in the Journal of the American Water Works Association.[3]

A number of excellent articles are available that discuss the stability and solubility of inorganic arsenic in various water environments.[5,6,7] The depth of these articles is an indication of the complexity of arsenic chemistry. In a natural water system, however, it is demonstrated that arsenic would most commonly be found in +5 and +3 oxidation states. A recent article by Gupta and Chen[8] presents the experimental results of using activated alumina, bauxite, and carbon as sorbents for arsenic in batch equilibrium tests. One of the base waters used in this study was fresh water to which was added concentrations of $As^{+3}$ in the form $NaAsO_2$ and $As^{+5}$ in the form $Na_2HAsO_4$. Their data show that activated alumina has about 20 times greater capacity for removal of $As^{+5}$ than for $As^{+3}$. They conclude that removal of arsenic from waste waters to meet water quality criteria is technically feasible.



In 1978, Rubel and Hager and the Aluminum Company of America conducted a pilot plant experiment on a potable water test well that contained 2 mg/L arsenic and 1 mg/L fluoride. Reports on this work have not yet been published, principally because the oxidation states of the test water were not identified. The work, however, was significant in that it demonstrated (1) that the activated alumina had a capacity for arsenic removal on this water comparable to that experienced with fluoride in fluoride-contaminated water, and (2) that there was a problem associated with regenerating the activated alumina. A serious question developed concerning the ability of activated alumina to remove excessive levels of two contaminants in combination in a single water supply. Specifically, arsenic is not removed from an activated alumina treatment bed during regeneration as easily as fluoride. This has also been reported for test work by Bellack.[4] Our tests indicated that higher sodium hydroxide concentrations were required to remove arsenic from activated alumina than the 1% caustic concentration used for fluoride removal at the full-scale fluoride removal plants. The pilot work also showed that arsenic retained on the activated alumina after regeneration interfered with the removal of fluoride during subsequent treatment runs.

To determine the extent of this interference, a pilot plant study program was established to investigate the performance of the activated alumina fluoride removal process on a water supply that contained excessive levels of both fluoride and arsenic. Through the cooperation of the Arizona Department of Health Services, a community that met the water criteria was located, and planning was initiated. The Why Utility Corporation at Why, Arizona, has a water supply with a history of excessive levels of high fluoride (2.4 to 3.3 mg/L) and arsenic (0.10 to 0.17 mg/L). Complete water analyses are included in Appendix C. On April 4, 1978, the Why Utility Corporation granted permission to perform the desired pilot test program. This report covers Phases I and II of the test program. Phase I included three treatment runs and regenerations for a single-stage treatment system. Phase II included three treatment runs and separate regenerations of each stage of a two-stage treatment system. During the course of the pilot test work in this report, the fluoride level was approximately 3.0 mg/L (maximum allowable is 1.4 mg/L for this climate), and the arsenic level was approximately 0.15 mg/L.

## SECTION 2

## CONCLUSIONS

Phase I of the pilot plant program demonstrated that high arsenic (0.14 ppm) in combination with high fluoride (3 ppm) in a single potable water supply degrades the efficiency of the activated alumina for fluoride removal. The amount of fluoride being adsorbed by the activated alumina after two regenerations in the pilot plant was one-half to two-thirds the values that have been observed in operating fluoride plants and previous fluoride removal pilot studies. These experiments also demonstrated that using a 1% sodium hydroxide solution for the regeneration fluid left approximately 25% of the adsorbed fluoride and 70% of the adsorbed arsenic on the activated alumina. A 4% sodium hydroxide solution, however, removed quantities of fluoride and arsenic almost equivalent to that which had been adsorbed on the previous treatment run.

In Phase II of the pilot study, a two-stage treatment process was tested. These experiments demonstrated that for the particular potable water concentrations being tested, arsenic continues to be adsorbed on the activated alumina after the fluoride capacity is reached. Thus arsenic is preferentially adsorbed on activated alumina. The fluoride removal capacity of the first column was approximately 4,300 $g/m^3$, or a third higher than that shown in the Phase I study, because in the Phase II study, the first column did continue to adsorb flouride after fluoride breakthrough. The fluoride removal capacity of the second column was approximately 3,300 $g/m^3$, which was lower than expected. The use of a 4% sodium hydroxide regeneration solution in column one and a 1% solution in column two resulted in acceptable alumina regenerations. A much longer pilot study beyond the scope of this project would be necessary to optimize processing variables.

No attempt was made in these studies to purposely alter the fluoride or arsenic concentrations or oxidation states. Therefore, no conclusions can be drawn from these data on the capacity of activated alumina for arsenic removal or of the effect that a change in the relative concentrations of the two contaminants might have on the activated aluminas useful adsorptive capacity. However, these pilot studies do demonstrate the feasibility of removing both arsenic and fluoride from a potable water system with activated alumina.

Analysis of the 4% sodium hydroxide regeneration solution indicates that a significantly higher percentage of the activated alumina is solubilized by this strength caustic. The authors estimate that an annual 10% replacement of activated alumina would be necessary in the proposed two-tower system, compared with 3% replacement experienced in fluoride removal plants that use 1% caustic regeneration solutions.

Limited analyses of water samples for arsenic oxidation states show that the test water contained 90% $As^{+5}$-10% $As^{+3}$, and that more than 97% of the $As^{+5}$ and 60% of the $As^{+3}$ was being removed by the activated alumina column.

The estimated operating costs of systems treating water for small towns (1,000 to 10,000 persons) varies from 4¢ to 5.5¢/kL (15¢ to 21¢/1,000 gal). These costs are approximately 30% higher than those experienced in plants removing fluoride only. Estimated capital equipment costs for these same systems varies from $200,000 to $800,000.

## SECTION 3

## DESCRIPTION OF TEST SITE AND APPARATUS

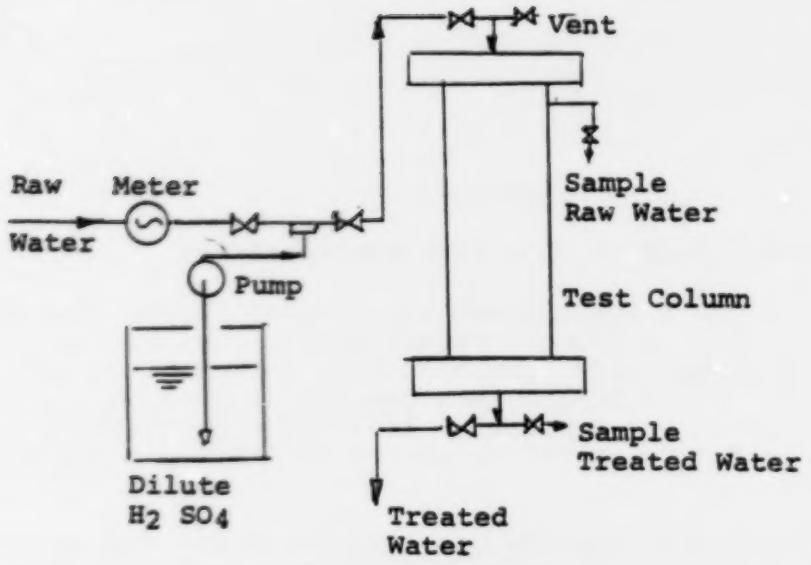
Why, Arizona, is a small community located 213 km west of Tucson, Arizona. The terrain is desert with rugged mountains. The climate is hot and arid. The community is unincorporated. Except for copper mining at Ajo, Arizona, 17 km away, there are no major industries. The population includes approximately 100 permanent residents, which can expand to 1,000 persons during vacation seasons.

The Why Utility Corporation provides the water supply for the community. There are 75 meter connections on the system. One deep well provides the entire water supply. This well is equipped with a pump that delivers water at the rate of 3.8 L/s to an interim storage tank at the well site.

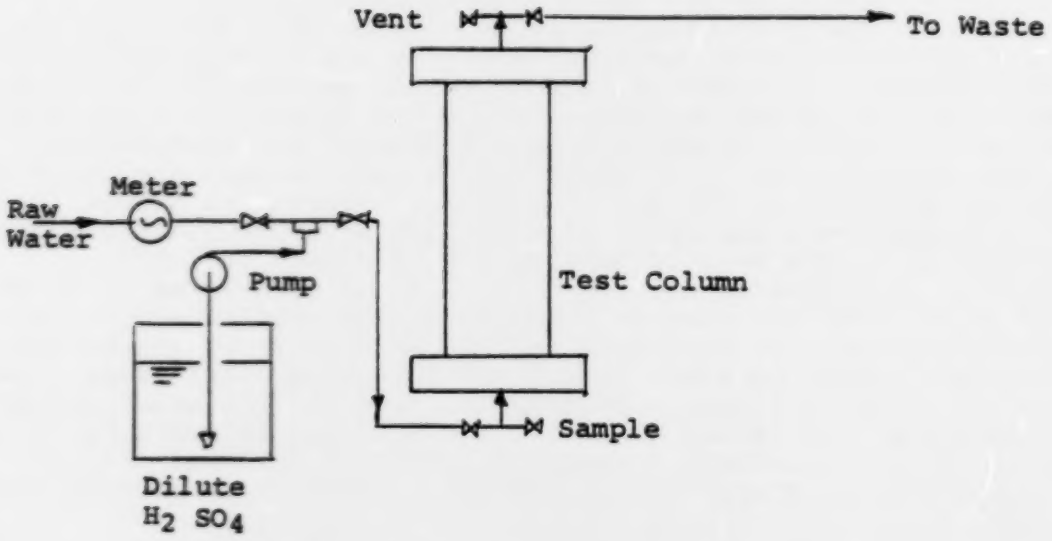
A distribution pump delivers water to a pressurization tank on a hill from which the water is distributed. The annual consumption for the community is 24,000 kL. The average daily consumption is 66 kL; maximum daily consumption is 95 kL.

Raw water used for testing was taken from the interim storage tank. The raw water was metered (flow rate and total flow) by a calibrated flow totalizer and then run through the treatment system. By means of plastic valves and hoses, the raw water was directed either downflow through the system for treatment and rinse, or upflow through the test column(s) for backwash and rinse (see Figures 1, 2, and 3). The test columns are 25-cm diameter, schedule 40 PVC by 1.5 m high, supported on a wood frame. The inside cross sectional area is 0.05 $m^2$. The treatment beds contained in the test columns were 0.56 m deep or 0.028 $m^3$ (1 $ft^3$) in volume of Alcoa F-1 grade (0.30 to 0.59 mm or 28 to 48 mesh) activated alumina. The activated alumina weight was 24 kg per bed. An acid feed system (consisting of batch tank, chemical pumps, chemical tubing and injection check valves) injected dilute sulfuric acid solution into the raw water for pH adjustment. In Phases I and II, the acid was injected prior to entry to the treatment column. In Phase II acid was also injected between stages during the post regeneration neutralization step.

After completion of a treatment run, each treatment bed was regenerated. The raw water supply was shut off and disconnected

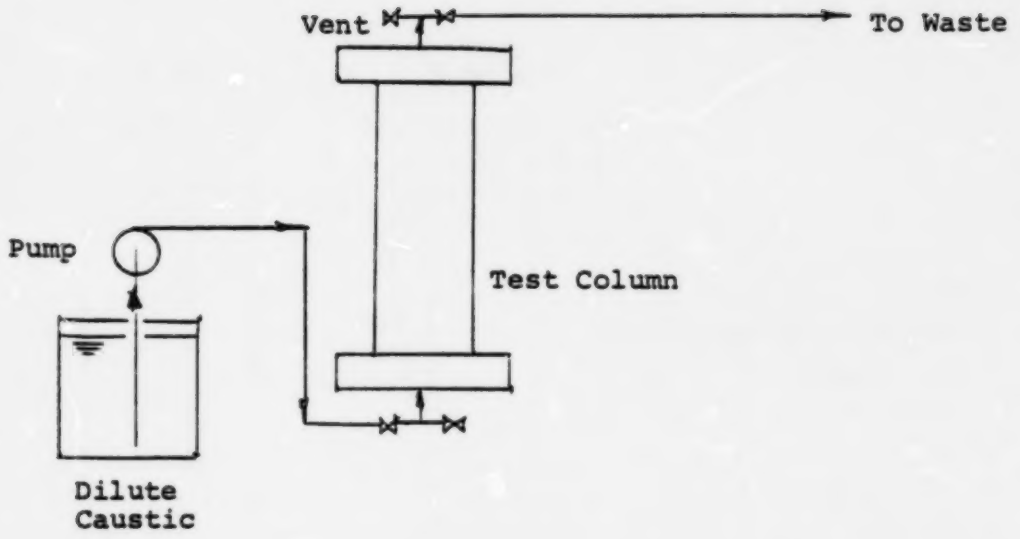



Treatment & Downflow Rinse Schematic

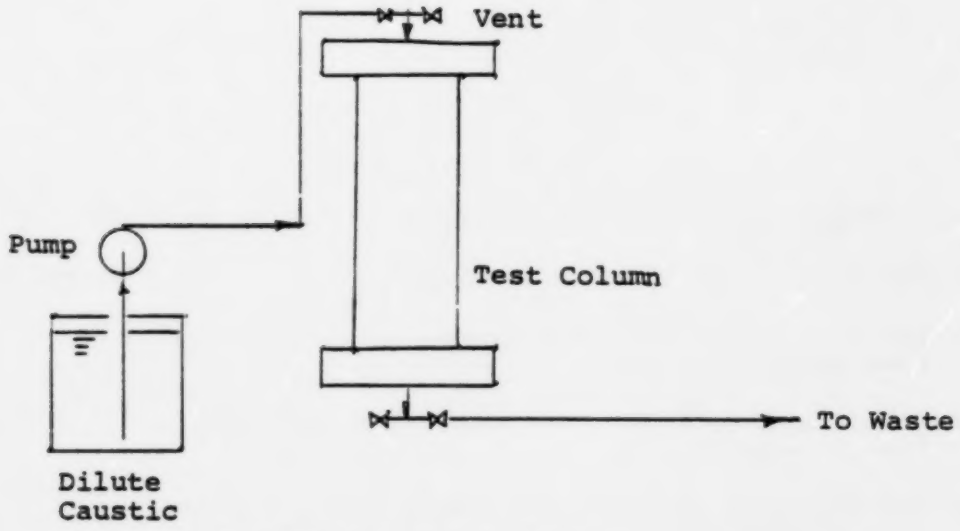



Backwash & Upflow Rinse Schematic

Figure 1. Process schematic flow diagrams - Phase I.

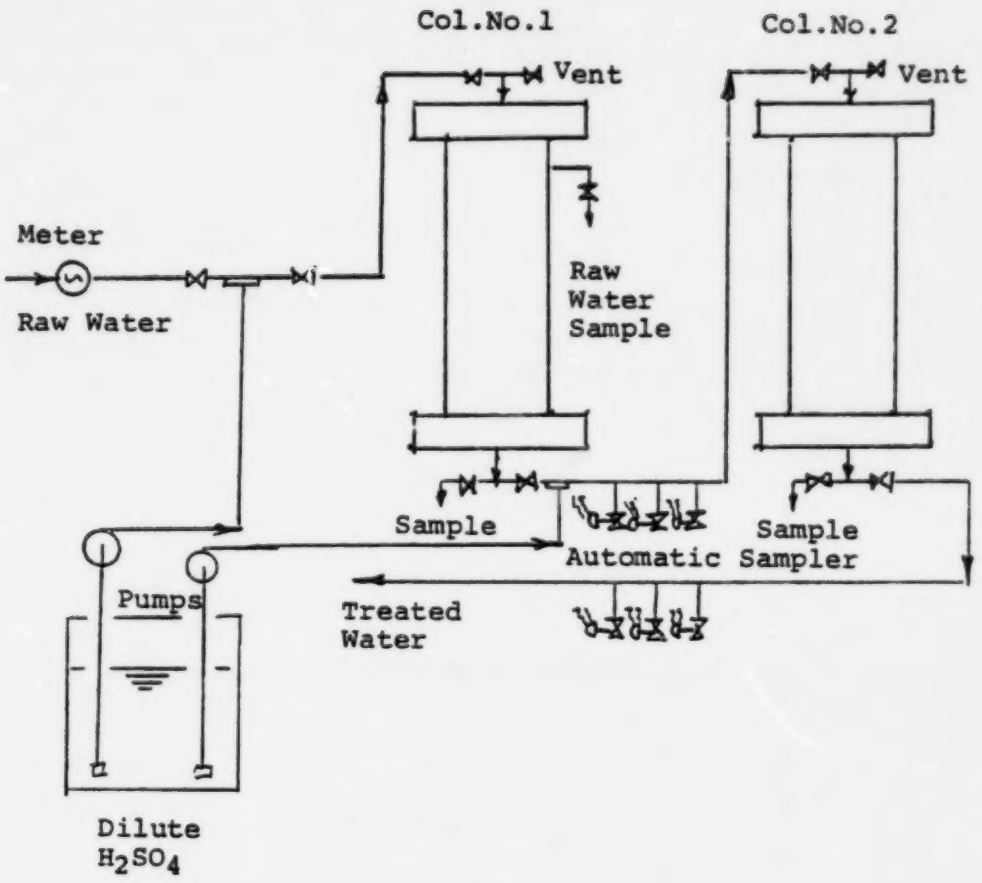



Upflow Regeneration




Downflow Regeneration

Figure 2. Regeneration process schematic flow diagrams - Phase I.




Note: Treatment schematic for Phase II is as follows:

(1) Downflow rinse schematic same as Phase I (see Figure 1).

(2) Backwash & upflow rinse schematic same as Phase I (see Figure 1).

(3) Upflow regeneration schematic same as Phase I (see Figure 2).

(4) Downflow regeneration schematic same as Phase I (see Figure 2).

Figure 3. Process schematic flow diagrams - Phase II.

and a separate dilute caustic soda feed system was connected to the treatment column being regenerated. This system (similar to the acid feed system) consisted of a batch tank, chemical pump, and chemical tubing. Regeneration wastewater was collected in 55-gallon drums in which contaminant levels were measured. Toxic wastes were transported to a lined waste evaporation pond.

The pilot test equipment was mounted in a mobile trailer which was set at the well site. This trailer also housed a mobile water testing laboratory which was primarily set up for analysis of fluoride (SPADNS), arsenic (Silver DDC) and pH. During the test program duplicate samples were collected and mailed to both the Alcoa Laboratories in Pittsburgh, Pennsylvania and the EPA Laboratory in Cincinnati, Ohio.

## SECTION 4

## EXPERIMENTAL RESULTS

Data for the test program are tabulated in Appendix A for Phase I and Appendix B for Phase II of this report.

During Phase I the treatment column was used for three adsorption cycles and caustic regenerations. The treatment flow rate was maintained at approximately 5.7 L/m throughout each treatment run. Each run was continuous until fluoride breakthrough. Fluoride breakthrough was defined as the point where the fluoride concentration exceeded an individual sample analysis of 2.4 mg/L or the point at which the average concentration of treated water through the column exceeded 1.1 mg/L fluoride. A summary of the experimental results is given in Table 1. From this table it can be seen that in each treatment run there was a deterioration in the activated alumina's capacity for fluoride removal. There was no evidence of arsenic saturation in the treatment bed during any of the runs.

The first treatment run showed an acceptable fluoride capacity of over 4,600 $g/m^3$ (2,000 $grains/ft^3$). Arsenic loading on the bed at that point was 340 $g/m^3$ (149 $grains/ft^3$). The 0.028 $m^3$ of activated alumina treated 64 kL (17,000 gal) of water. The first regeneration was conducted as if it were a fluoride removal plant with a 1% caustic solution. Both fluoride and arsenic recovery were inadequate in that only 71% of the fluoride and 41% of the arsenic was removed. During the second treatment run the new amount of fluoride retained on the activated alumina bed was approximately 27% lower than in the first run but the total amount of fluoride retained has approximately the same. The arsenic concentration on the bed increased to 480 $g/m^3$. The second regeneration employed 33% more of the 1% NaOH regenerative solution than in the first regeneration. Eighty-three percent of the retained fluoride was removed in this regeneration, but only 32% of the retained arsenic was removed. On the third treatment run the new fluoride retained was 35% lower than the first treatment. The arsenic retained had increased to 580 $g/m^3$. The regeneration prccedure was modified for the third regeneration to employ a sodium hydroxide concentration of 4%. This treatment effected a 92% removal of the total retained fluoride and 44% removal of the total retained arsenic.

TABLE 1. PHASE I PILOT PLANT FLUORIDE AND ARSENIC REMOVAL SUMMARY

| Mode | Fluoride added to treatment bed* ($g/m^3$) | Fluoride removed from treatment bed ($g/m^3$) | Fluoride retained in treatment bed ($g/m^3$) | Arsenic added ($g/m^3$) | Arsenic removed ($g/m^3$) | Arsenic retained ($g/m^3$) | Treated water (kL) | Waste-water (kL) | % Waste-water |
|---|---|---|---|---|---|---|---|---|---|
| Treatment Run No. 1 | 4,652 | - | 4,652 | 340 | - | 340 | 64.2 | - | - |
| Regenera-tion No. 1 | - | 3,300 | 1,352 | - | 140 | 200 | - | 1.8 | 2.8 |
| Treatment Run No. 2 | 3,378 | - | 4,730 | 275 | - | 485 | 51.9 | - | - |
| Regenera-tion No. 2 | - | 3,938 | 792 | - | 153 | 332 | - | 1.4 | 2.8 |
| Treatment Run No. 3 | 3,014 | - | 3,806 | 247 | - | 579 | 46.5 | - | - |
| Regenera-tion No. 3 | - | 3,506 | 300 | - | 256 | 323 | - | 1.4 | 3.0 |
| Total | - | - | 300 | - | - | 323 | 162.6 | 4.6 | 2.8 |

*$g/m^3$ x 0.437 - grains/$ft^3$.

These three sorption and regeneration runs confirmed the decrease in fluoride capacity and difficulty of removing arsenic from the activated alumina which had been observed in the earlier pilot plant runs. In an effort to improve treatment efficiency and eventual operating cost economics, the decision was made to extend the test program into a second phase.

In Phase II the test apparatus was modified to provide two treatment beds in series (Figure 3). Each column was charged with 0.028 $m^3$ of fresh activated alumina. The data collected in the unreported pilot plant run on high arsenic water had shown that arsenic was preferentially adsorbed by the activated alumina and that the bed would continue to remove arsenic even after it was saturated with fluoride. Thus in a two-column system, the first stage is designated as a sacrificial bed which is provided primarily for the removal of arsenic. The second stage is employed primarily for the removal of fluoride.

During the course of the Phase II experimental runs, samples were taken between columns as a means of checking to make sure that only a negligible amount of arsenic was in the first column effluent prior to fluoride saturation of the second stage. The treatment flow rate was maintained between 4.7 and 5.7 L/m throughout each treatment run. Each run was continuous until second stage fluoride breakthrough dictated completion of the run.

During the Phase II experimental runs, small process upsets occurred in treatment runs No. 1 and 2. These upsets are noted in the tabulated data in Appendix B. While these upsets may have affected the absolute numbers determined in these two experimental runs, the authors do not believe that they infringe in any way on the final report conclusions.

Experimental data for Phase II runs are summarized in Table 2. A plot of the experimental data from the number three treatment run is shown in Figure 4. These data confirm that the first column preferentially adsorbed arsenic with the result that during the majority of each of the three runs the arsenic concentration leaving the first column was less than 5 ppb (the detection limit of our analytical method) and in no case did it exceed 11 ppb at the end of a run. The run was terminated as in Phase I study when fluoride concentration in the effluent from the second column exceeded 1.1 mg/L average concentration for all treated water or 2.4 mg/L for an individual sample. The average treated water analyses in these three runs was approximately 0.7 mg/L.

The scope of work for Phase II of this project included three treatment regeneration cycles. The data obtained demonstrate the technical feasibility of the two column system which

TABLE 2: PHASE II PILOT PLANT FLUORIDE AND ARSENIC REMOVAL SUMMARY

| Mode | F added to Col. No.1 ($g/m^3$) | F removed from Col. No.1 ($g/m^3$) | F retained in Col. No.1 ($g/m^3$) | As added to Col. No.1 ($g/m^3$) | As removed from Col. No.1 ($g/m^3$) | As retained in Col. No.1 ($g/m^3$) | F added to Col. No.2 ($g/m^3$) | F removed from Col. No.2 ($g/m^3$) | F retained in Col. No.2 ($g/m^3$) | Treated water (k/L) | Waste-water (k/L) | % Waste | 66°B' $H_2SO_4$ used (L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Treatment No. 1 | 6080 | - | 6080 | 593 | - | 593 | 5293 | - | 5293 | 120.6 | - | - | 6.5 |
| Regen. No. 1 | - | 5576 | 504 | - | 346 | 249 | - | 3577 | 1716 | - | 2.0 | 1.7 | - |
| Treatment No. 2 | 4357 | - | 4861 | 476 | - | 723 | 3527 | - | 5243 | 100.2 | - | - | 5.0 |
| Regen. No. 2 | - | 4298 | 563 | - | 360 | 363 | - | 3108 | 2135 | - | 2.3 | 2.3 | - |
| Treatment No. 3 | 4333 | - | 4896 | 491 | - | 854 | 3379 | - | 5514 | 102.5 | - | - | 5.0 |
| Regen. No. 3 | - | 4577 | 319 | - | 374 | 480 | | 3259 | 2255 | - | 2.0 | 2.0 | - |
| Total | - | - | 319 | - | - | 480 | - | - | 2255 | 322.8 * | 6.3 | 2.0 | 16.0† |

*18 L 50% NaOH @ 20¢/L = $3.60
Therefore caustic cost was 1.12¢/kL treated water.

†16 L 66°B'$H_2SO_4$ @ 6.6¢/L = $1.06
Therefore acid cost was 0.33¢/kL treated water.

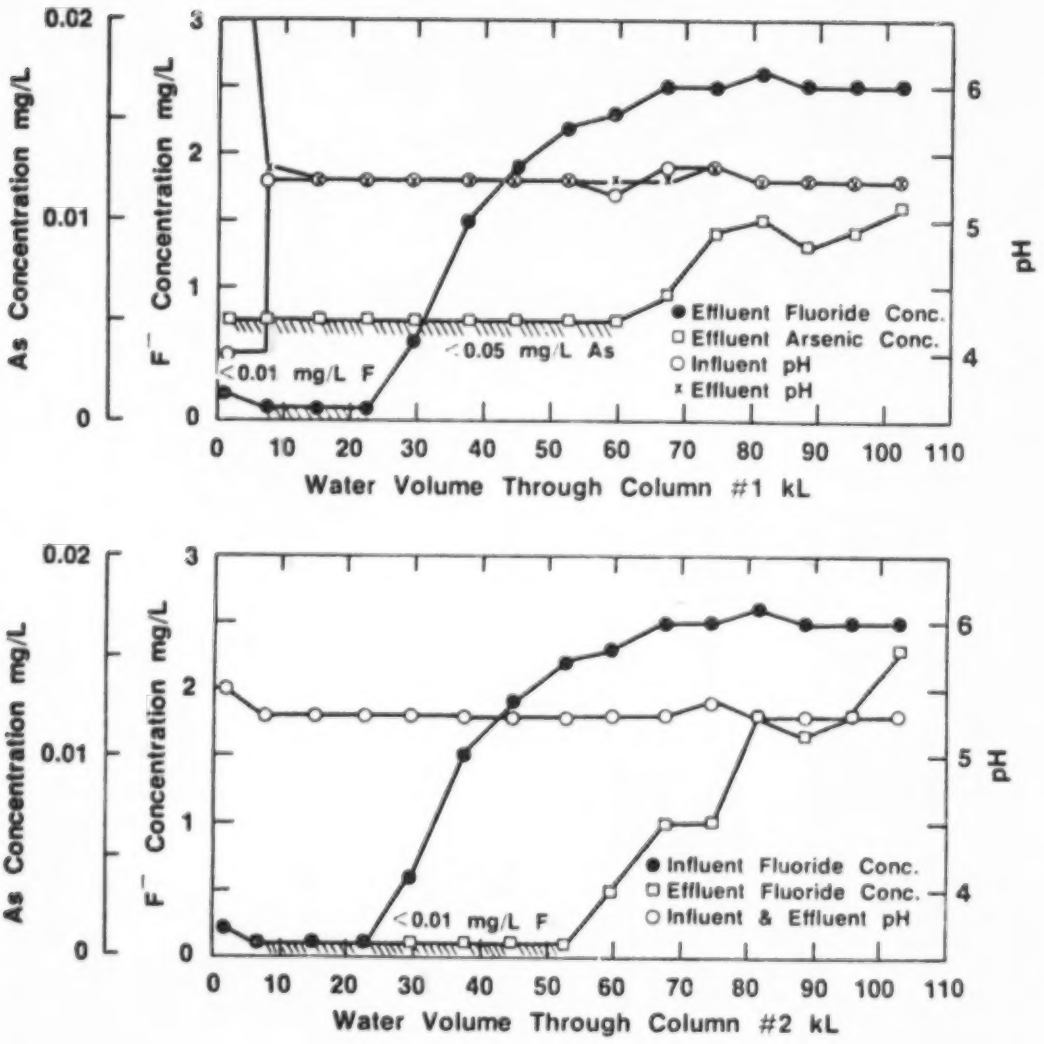



Figure 4. Plots of Phase II run 3 water concentrations. Raw water 2.8 mg/L $F^-$, 0.14 mg/L As and pH 7.5. Each column held 0.028 $m^3$ of activated alumina.

was the purpose of this phase of the project. Further experimental work to determine the number of cycles the first column can be effective in removing As is desirable; however, the time and expense would far exceed the limits of this project. The investigation into the lower than expected F removal capacity of column two is also desirable, but again beyond the limits of this project. Cost projections appearing later in this report are based upon the limited data obtained.

Data on the losses of alumina with each Phase II regeneration were measured and are shown in Table 3.

TABLE 3. DATA ON THE DISSOLUTION OF ALUMINA DURING REGENERATION

| Regeneration | Column | Wt % of total bed in solution |
|---|---|---|
| 1 | 1 | 2.9 |
| | 2 | 1.2 |
| 2 | 1 | 1.9 |
| | 2 | 0.5 |
| 3 | 1 | 1.5 |
| | 2 | 0.6 |

The above data show alarmingly high values of alumina being removed from the activated alumina bed. However, a decreasing trend is evident with each regeneration. It is known that early regenerations of fresh activated alumina do remove unusually high amounts of material because the individual alumina particles have attached pieces which become displaced by attrition. Plant experience with regenerations similar to second column regenerations with 1% caustic has resulted in the need for approximately 3% bed replacement per year. Based on the facts in Table 3 and plant experience, it is the authors' estimate that an overall bed replacement of 10% for the two columns should be anticipated with the majority of that alumina being needed in the first column.

During the course of Phase II experiments, a limited number of samples were sent to the chemistry department at the University of Arizona for analysis of the arsenic oxidation stages present in raw water, treated water, and regeneration solutions. The results are summarized in Table 4 below.



TABLE 4. ARSENIC OXIDATION STATES

| Sample | % Distribution | |
|---|---|---|
| | $As^{+3}$ | $As^{+5}$ |
| Raw water | 10 | 90 |
| Treated water | 60 | 40 |
| Regenerated solution | 5 | 95 |

The articles in the literature[5,6,7] which discuss the oxidation states of arsenic in water systems conclude that well water samples would be expected to have the majority of the arsenic present as $As^{+3}$. Table 4 indicates that this particular water is just the opposite with 90% of the arsenic present as $As^{+5}$. The authors cannot verify that $As^{+5}$ is or is not the typical form of arsenic present in Arizona wells contaminated with arsenic. The article by Gupta and Chen[8] indicates that activated alumina should be much more effective in removal of $As^{+5}$ than $As^{+3}$. The effluent samples listed in Table 4 were taken near the end of treatment runs when the arsenic level was around 9 ppb. The data showing 60% $As^{+3}$ and 40% $As^{+5}$ do confirm that $As^{+5}$ form is being removed to a much higher degree than the $As^{+3}$ form. If it is assumed that none of the $As^{+3}$ is oxidized to $As^{+5}$ in the course of pH adjustment and movement through the activated alumina bed, at the end of the run when the samples were taken, at least 60% of the $As^{+3}$ is being removed by the activated alumina and 97% of the $As^{+5}$. The above data would also say that during the course of a treatment run when the effluent values from the first column were $\leq$ 5 ppb As that more than 70% of the $As^{+3}$ was being removed (assuming that all effluent As was in the form of $As^{+3}$). The regeneration solution results are interesting in that the form of arsenic present in these solutions is greater than 95% +5. Using the raw water and effluent analyses, the calculated value expected in the regeneration solution would be a 7% to 93% split between $As^{+3}$ and $As^{+5}$. One could conclude that this difference between calculated and measured values is (a) not significant because of the accuracy of the analytical techniques, (b) due to a transformation of $As^{+3}$ to $As^{+5}$ by the combination of treatment and regeneration procedures, and (c) the caustic regeneration is not effective in removing $As^{+3}$ from the activated alumina. A longer experimental program with field-mounted analytical capability would be necessary before there can be confidence in any of the above conclusions.

## SECTION 5

## COST ESTIMATES

Operating and capital cost estimates are based on Phase II pilot plant data. Cost estimates have been developed for this report using the following design criteria:

1) Maximum consumption 1.1 kL (300 gal) per day per person
2) Average consumption 640 L (170 gal) per day per person
3) Average fluoride - raw water - 3.0 mg/L
4) Average fluoride - treated water - 1.0 mg/L
5) Minimum fluoride capacity for activated alumina - 2300 $g/m^3$ (1,000 $grains/ft^3$)
6) Activated alumina replacement rate - 10%/year
7) Wastewater pond evaporation rate - 1.8 m/year
8) 50% NaOH delivered cost - 20¢/L
9) 66° B' $H_2SO_4$ delivered cost - 6.6¢/L
10) Electric utility rate - 5¢/kWh
11) Plant operating labor rate - $6/hr

A typical plant layout is illustrated on Figure 5. Preliminary operating and capital costs for small systems are tabulated in Tables 5 and 6. The operating costs of 4.0 to 5.5¢/kL are approximately 30% higher for removal of the combined fluoride and arsenic than for fluoride removal only. The capital costs are approximately the same. As pointed out in the design criteria, cost estimates assume that the wastewater from the media regeneration will be contained in an evaporation pond.

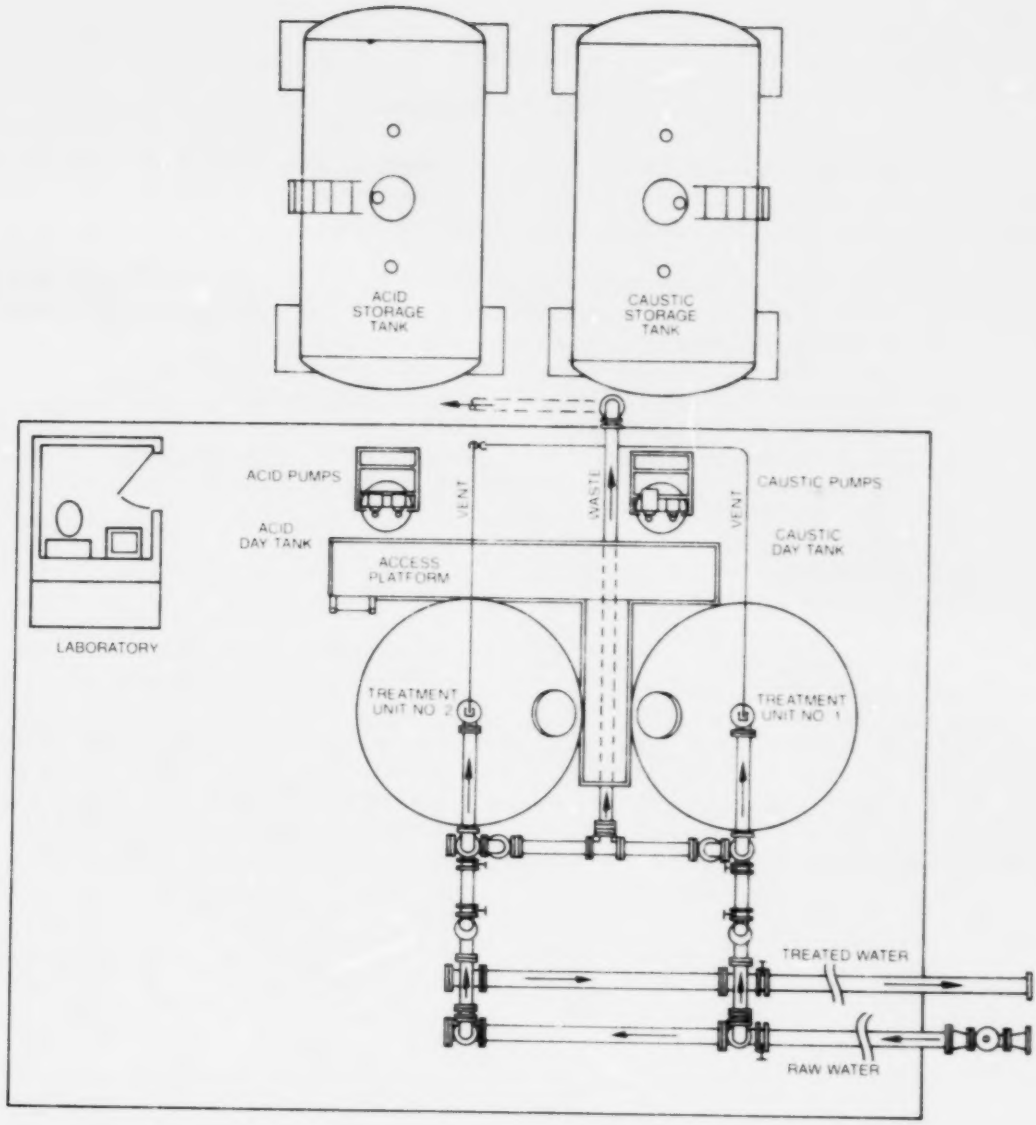



Figure 5. Typical fluoride and arsenic removal plant plan.

TABLE 5. PRELIMINARY OPERATING COST ESTIMATES FOR SMALL SYSTEMS*

| Item | Population 1,000 ¢/kL | 1,000 ¢/1,000 gal | 5,000 ¢/kL | 5,000 ¢/1,000 gal | 10,000 ¢/kL | 10,000 ¢/1,000 gal |
|---|---|---|---|---|---|---|
| Acid | 0.5 | 2 | 0.5 | 2 | 0.5 | 2 |
| Caustic soda | 1.3 | 5 | 1.3 | 5 | 1.3 | 5 |
| Operation labor | 2.6 | 10 | 1.0 | 4 | 0.8 | 3 |
| Electric utility | 0.3 | 1 | 1.0 | 1 | 0.3 | 1 |
| Media replacement | 0.5 | 2 | 0.5 | 2 | 0.8 | 3 |
| Spare parts & misc. | 0.3 | 1 | 0.3 | 1 | 0.3 | 1 |
| Total | 5.5 | 21 | 4.0 | 15 | 4.0 | 15 |

*Based on two-stage treatment system.

TABLE 6. PRELIMINARY CAPITAL COST ESTIMATES FOR SMALL SYSTEMS

| Item | Population 1,000 | 5,000 | 10,000 |
|---|---|---|---|
| Treatment vessels | $20,000 | $60,000 | $120,000 |
| Treatment media | 9,000 | 42,000 | 84,000 |
| Pipe, fittings, valves and instrumentation | 18,000 | 40,000 | 55,000 |
| Chemical storage tanks | 15,000 | 20,000 | 20,000 |
| Chemical system equipment | 8,000 | 11,000 | 12,000 |
| Installation of equipment | 32,000 | 50,000 | 75,000 |
| Prefab building, slabs and foundations | 28,000 | 60,000 | 75,000 |
| Lined toxic waste evaporation pond | 40,000 | 150,000 | 280,000 |
| Contingencies | 20,000 | 35,000 | 49,000 |
| Engineering and fees | 20,000 | 35,000 | 50,000 |
| Total | $210,000 | $500,000 | $820,000 |

## REFERENCES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5. Sergeyeva, E. I. and Khadakovskiy, I. L., Physicochemical Conditions of Formation of Native Arsenic in Hydrothermal Deposits, Geochemistry International (Geokhimiga 7), 846-859.

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# APPENDIX A. FLUORIDE/ARSENIC REMOVAL PROJECT - PHASE I

TABLE A-1. TREATMENT RUN NO. 1

| Date | Time | Δ Flow (kL) | Total flow (kL) | Adjusted raw water (pH) | Treated water (pH) | Raw water F (mg/L) | Treated water F (mg/L) | F removed in increment (g) | Total F removed (g) | Raw water As (mg/L) | Treated water As (mg/L) | As removed in increment (g) | Total As removed (g) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6/13 | 1530 | - | - | 5.6 | 7.6 | 2.9 | 0.9 | - | - | 0.15 | <0.01 | - | - |
| 6/13 | 2000 | 1.5 | 1.5 | 5.7 | 7.3 | 2.9 | 0.3 | 3.5 | 3.5 | 0.15 | <0.01 | 0.23 | 0.23 |
| 6/14 | 0400 | 2.8 | 4.3 | 5.6 | 6.5 | 2.9 | 0.2 | 7.5 | 11.0 | 0.15 | <0.01 | 0.42 | 0.65 |
| 6/14 | 1100 | 2.1 | 6.4 | 5.6 | 5.8 | 2.9 | <0.1 | 5.7 | 16.7 | 0.15 | <0.01 | 0.32 | 0.97 |
| 6/14 | 2000 | 3.1 | 9.5 | 5.4 | 5.6 | 2.9 | <0.1 | 8.8 | 25.5 | 0.15 | <0.01 | 0.47 | 1.44 |
| 6/15 | 0600 | 1.8 | 11.3 | 5.4 | 5.5 | 2.9 | <0.1 | 5.0 | 30.5 | 0.15 | <0.01 | 0.26 | 1.70 |
| 6/15 | 1100 | 1.5 | 12.8 | 5.4 | 5.6 | 2.9 | <0.1 | 4.3 | 34.8 | 0.15 | <0.01 | 0.23 | 1.93 |
| 6/15 | 1700 | 2.9 | 15.7 | 5.4 | 5.6 | 2.9 | <0.1 | 8.0 | 42.8 | 0.15 | <0.01 | 0.43 | 2.37 |
| 6/16 | 0200 | 3.0 | 18.7 | 5.4 | 5.6 | 2.9 | <0.1 | 8.5 | 51.3 | 0.15 | <0.01 | 0.45 | 2.82 |
| 6/16 | 0900 | 2.5 | 21.3 | 5.4 | 5.6 | 2.9 | <0.1 | 7.1 | 58.4 | 0.15 | <0.01 | 0.38 | 3.20 |
| 6/16 | 1600 | 2.8 | 24.1 | 5.4 | 5.5 | 2.9 | <0.1 | 7.9 | 66.3 | 0.15 | <0.01 | 0.42 | 3.62 |
| 6/16 | 2100 | 1.8 | 25.9 | 5.4 | 5.4 | 2.9 | 0.2 | 4.8 | 71.1 | 0.15 | <0.01 | 0.26 | 3.88 |
| 6/17 | 0700 | 3.8 | 29.7 | 5.4 | 5.4 | 2.9 | 0.4 | 10.0 | 81.1 | 0.15 | <0.01 | 0.58 | 4.46 |
| 6/17 | 1245 | 2.4 | 32.1 | 5.4 | 5.5 | 2.9 | 0.5 | 6.0 | 87.1 | 0.15 | <0.01 | 0.37 | 4.83 |
| 6/17 | 1915 | 2.6 | 34.7 | 5.4 | 5.4 | 2.9 | 0.7 | 6.0 | 93.1 | 0.15 | <0.01 | 0.39 | 5.22 |
| 6/18 | 0300 | 3.1 | 37.8 | 5.4 | 5.4 | 2.9 | 0.9 | 6.4 | 99.5 | 0.15 | <0.01 | 0.46 | 5.68 |
| 6/18 | 2100 | 2.5 | 40.3 | 5.4 | 5.4 | 2.9 | 1.1 | 4.8 | 104.3 | 0.15 | <0.01 | 0.38 | 6.06 |
| 6/19 | 0700 | 3.7 | 44.0 | 5.4 | 5.4 | 2.9 | 1.3 | 6.3 | 110.6 | 0.15 | <0.01 | 0.56 | 6.62 |
| 6/19 | 1300 | 2.6 | 46.6 | 5.4 | 5.4 | 2.9 | 1.5 | 3.9 | 114.5 | 0.15 | <0.01 | 0.40 | 7.02 |
| 6/20 | 2000 | 3.2 | 49.8 | 5.4 | 5.4 | 2.9 | 1.6 | 4.2 | 118.7 | 0.15 | <0.01 | 0.46 | 7.48 |
| 6/21 | 1000 | 5.2 | 55.0 | 5.4 | 5.4 | 2.9 | 1.9 | 6.0 | 124.7 | 0.15 | <0.01 | 0.78 | 8.26 |
| 6/21 | 1830 | 3.7 | 58.7 | 5.4 | 5.4 | 2.9 | 2.2 | 3.1 | 127.8 | 0.15 | <0.01 | 0.55 | 8.81 |
| 6/22 | 0800 | 5.5 | 64.2 | 5.4 | 5.4 | 2.9 | 2.4 | 3.3 | 131.1 | 0.15 | <0.01 | 0.83 | 9.64 |

TABLE A-2. REGENERATION NO. 1:
DOUBLE REGENERATION PROCEDURE EMPLOYING 1% SODIUM HYDROXIDE, JUNE 22, 1978

| Step | Flow rate (L/m) | Time (min) | Flow (L) | 55-gal Waste drum no. | Fluoride | | Arsenic | | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | mg/L | g/drum | mg/L | g/drum | |
| Backwash | 18.9 | 16 | 302 | | N.A. | N.A. | N.A. | N.A. | Some turbidity |
| Upflow regeneration | 1.9 | 36 | 68 | 1 | 310 | 64.6 | 9.2 | 1.94 | |
| Upflow rinse | 5.7 | 25 | 140 | 1 | 310 | 64.6 | 9.2 | 1.94 | |
| Upflow rinse | 5.7 | 36 | 208 | 2 | 80 | 16.8 | 4.4 | 0.84 | |
| Upflow rinse | 5.7 | 36 | 208 | 3 | 20 | 4.1 | 0.4 | 0.07 | |
| Upflow rinse | 5.7 | 36 | 208 | 4 | 6 | 1.2 | - | - | |
| Downflow regeneration | 1.9 | 36 | 68 | 5 | 25 | 5.2 | 4.7 | 0.97 | |
| Downflow rinse | 1.5 | 98 | 140 | 5 | 25 | 5.2 | 4.7 | 0.97 | |
| Downflow neutralization | 5.7 | 36 | 208 | 6 | 5 | 1.0 | 0.7 | 0.13 | Rinse water pH - 2.5 |
| Downflow neutralization | 5.7 | 36 | 208 | 7 | 2.5 | 0.5 | - | - | Rinse water pH - 2.5 |
| Total | | | 1,760 | - | - | 93.4 | - | 3.95 | |

TABLE A-3. TREATMENT RUN NO. 2

| Date | Time | Δ Flow (kL) | Total flow (kL) | Adjusted raw water (pH) | Treated water (pH) | Raw water F (mg/L) | Treated water F (mg/L) | F removed in increment (g) | Total F removed (g) | Raw water As (mg/L) | Treated water As (mg/L) | As removed in increment (g) | Total As removed (g) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6/26 | 1830 | - | - | 2.5 | 10.9 | 2.9 | 1.2 | - | - | 0.15 | <0.01 | - | - |
| 6/26 | 2100 | 0.9 | 0.9 | 2.5 | 9.9 | 2.9 | 0.4 | 1.9 | 1.9 | 0.15 | <0.01 | 0.14 | 0.14 |
| 6/26 | 2300 | 0.6 | 1.5 | 4.0 | 9.0 | 2.9 | 0.3 | 1.5 | 3.4 | 0.15 | <0.01 | 0.09 | 0.23 |
| 6/27 | 0700 | 2.9 | 4.4 | 5.5 | 6.4 | 2.9 | <0.1 | 7.7 | 11.1 | 0.15 | <0.01 | 0.42 | 0.65 |
| 6/27 | 1440 | 2.2 | 6.6 | 5.5 | 5.9 | 2.9 | <0.1 | 6.3 | 17.4 | 0.15 | <0.01 | 0.34 | 0.99 |
| 6/27 | 2045 | 2.4 | 9.0 | 5.5 | 5.8 | 2.9 | <0.1 | 6.8 | 24.2 | 0.15 | <0.01 | 0.36 | 1.35 |
| 6/28 | 0600 | 3.3 | 12.3 | 5.6 | 5.7 | 2.9 | <0.1 | 9.1 | 33.3 | 0.15 | <0.01 | 0.49 | 1.84 |
| 6/28 | 1130 | 1.8 | 14.1 | 5.5 | 5.6 | 2.9 | <0.1 | 5.1 | 38.4 | 0.15 | <0.01 | 0.27 | 2.11 |
| 6/28 | 2045 | 3.3 | 17.4 | 5.6 | 5.6 | 2.9 | 0.2 | 9.1 | 47.5 | 0.15 | <0.01 | 0.50 | 2.61 |
| 6/29 | 0600 | 3.4 | 20.8 | 5.5 | 5.6 | 2.9 | 0.6 | 8.6 | 56.1 | 0.15 | <0.01 | 0.52 | 3.13 |
| 6/29 | 1115 | 1.5 | 22.3 | 5.6 | 5.6 | 2.9 | 0.7 | 3.3 | 59.4 | 0.15 | <0.01 | 0.21 | 3.34 |
| 6/29 | 2215 | 3.7 | 26.0 | 5.5 | 5.6 | 2.9 | 0.9 | 7.7 | 67.1 | 0.15 | <0.01 | 0.56 | 3.90 |
| 6/30 | 0700 | 2.9 | 28.9 | 5.5 | 5.6 | 2.9 | 1.1 | 5.5 | 72.6 | 0.15 | <0.01 | 0.44 | 4.34 |
| 6/30 | 1130 | 1.5 | 30.4 | 5.5 | 5.6 | 2.9 | 1.3 | 2.6 | 75.2 | 0.15 | <0.01 | 0.23 | 4.57 |
| 6/30 | 2030 | 3.0 | 33.4 | 5.6 | 5.6 | 2.9 | 1.5 | 4.5 | 79.7 | 0.15 | <0.01 | 0.45 | 5.02 |
| 7/1 | 0620 | 3.2 | 36.6 | 5.5 | 5.6 | 2.9 | 1.7 | 4.2 | 83.9 | 0.15 | <0.01 | 0.48 | 5.50 |
| 7/1 | 1330 | 2.3 | 38.9 | 5.5 | 5.6 | 2.9 | 1.9 | 2.5 | 86.4 | 0.15 | <0.01 | 0.34 | 5.84 |
| 7/2 | 0900 | 6.1 | 45.0 | 5.5 | 5.6 | 2.9 | 2.1 | 4.9 | 91.3 | 0.15 | <0.01 | 0.93 | 6.77 |
| 7/2 | 2030 | 3.7 | 48.7 | 5.6 | 5.6 | 2.9 | 2.3 | 2.5 | 93.8 | 0.15 | <0.01 | 0.54 | 7.31 |
| 7/3 | 0700 | 3.3 | 52.0 | 5.5 | 5.5 | 2.9 | 2.4 | 1.8 | 95.6 | 0.15 | <0.01 | 0.49 | 7.80 |

TABLE A-4. REGENERATION NO. 2:
DOUBLE REGENERATION PROCEDURE EMPLOYING 1% SODIUM HYDROXIDE, JULY 4, 1978

| Step | Flow rate (L/m) | Time (min) | Flow (L) | 55-gal Waste drum no. | Fluoride | | Arsenic | | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | mg/L | g/drum | mg/L | g/drum | |
| Backwash | 22.7 | 15 | 341 | | N.A. | N.A. | N.A. | N.A. | Some turbidity |
| Upflow regeneration | 2.8 | 32 | 91 | 1 | 390 | 81.3 | 9.7 | 2.01 | |
| Upflow rinse | 5.7 | 20 | 117 | 1 | 390 | 81.3 | 9.7 | 2.01 | |
| Upflow rinse | 5.7 | 36 | 208 | 2 | 75 | 15.6 | 4.8 | 0.97 | |
| Upflow rinse | 5.7 | 36 | 208 | 3 | 17 | 3.6 | 0.7 | 0.13 | |
| Upflow rinse | 5.7 | 10 | 57 | 4 | 4 | 0.2 | - | - | |
| Downflow regeneration | 2.8 | 32 | 91 | 5 | 40 | 8.3 | 5.6 | 1.17 | |
| Downflow neutralization | 5.7 | 20 | 117 | 5 | 40 | 8.3 | 5.6 | 1.17 | Rinse water pH - 2.5 |
| Downflow neutralization | 5.7 | 36 | 208 | 6 | 12 | 2.5 | 0.4 | 0.06 | Rinse water pH - 2.5 |
| Total | | | 1,438 | - | - | 111.5 | - | 4.34 | |

TABLE A-5. TREATMENT RUN NO. 3

| Date | Time | Δ Flow (kL) | Total flow (kL) | Adjusted raw water (pH) | Treated water (pH) | Raw water F (mg/L) | Treated water F (mg/L) | F removed in increment (g) | Total F removed (g) | Raw water As (mg/L) | Treated water As (mg/L) | As removed in increment (g) | Total As removed (g) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7/4 | 1330 | - | - | 2.5 | 10.2 | 2.9 | 1.1 | - | - | 0.15 | <0.01 | - | - |
| 7/4 | 1600 | 0.8 | 0.8 | 4.0 | 9.0 | 2.9 | 0.7 | 1.6 | 1.6 | 0.15 | <0.01 | 0.12 | 0.12 |
| 7/4 | 2115 | 1.8 | 2.6 | 5.6 | 7.0 | 2.9 | 0.2 | 4.6 | 6.2 | 0.15 | <0.01 | 0.27 | 0.39 |
| 7/5 | 0600 | 2.9 | 5.5 | 5.5 | 5.8 | 2.9 | <0.1 | 7.9 | 14.1 | 0.15 | <0.01 | 0.43 | 0.82 |
| 7/5 | 1500 | 2.8 | 8.3 | 5.6 | 5.6 | 2.9 | <0.1 | 7.9 | 22.0 | 0.15 | <0.01 | 0.42 | 1.24 |
| 7/5 | 2030 | 1.7 | 10.0 | 5.6 | 5.6 | 2.9 | <0.1 | 4.6 | 26.6 | 0.15 | <0.01 | 0.26 | 1.50 |
| 7/6 | 0600 | 3.2 | 13.2 | 5.6 | 5.6 | 2.9 | <0.1 | 9.0 | 35.6 | 0.15 | <0.01 | 0.48 | 1.98 |
| 7/6 | 1100 | 1.6 | 14.8 | 5.6 | 5.6 | 2.9 | 0.1 | 4.7 | 40.3 | 0.15 | <0.01 | 0.36 | 2.34 |
| 7/6 | 2030 | 3.3 | 18.1 | 5.6 | 5.6 | 2.9 | 0.4 | 8.6 | 48.9 | 0.15 | <0.01 | 0.38 | 2.72 |
| 7/7 | 0630 | 3.6 | 21.7 | 5.5 | 5.6 | 2.9 | 0.7 | 8.6 | 57.5 | 0.15 | <0.01 | 0.45 | 3.27 |
| 7/7 | 1130 | 2.3 | 24.0 | 5.5 | 5.5 | 2.9 | 1.0 | 4.1 | 61.6 | 0.15 | <0.01 | 0.33 | 3.60 |
| 7/7 | 2115 | 2.8 | 26.8 | 5.5 | 5.5 | 2.9 | 1.3 | 5.1 | 66.7 | 0.15 | <0.01 | 0.44 | 4.04 |
| 7/8 | 0615 | 3.3 | 30.1 | 5.5 | 5.5 | 2.9 | 1.6 | 4.6 | 71.3 | 0.15 | <0.01 | 0.48 | 4.52 |
| 7/8 | 1530 | 3.3 | 33.4 | 5.5 | 5.5 | 2.9 | 1.9 | 3.9 | 75.2 | 0.15 | <0.01 | 0.51 | 5.03 |
| 7/9 | 0915 | 6.0 | 39.4 | 5.5 | 5.5 | 2.9 | 2.1 | 5.4 | 80.6 | 0.15 | <0.01 | 0.89 | 5.92 |
| 7/9 | 2000 | 3.1 | 42.5 | 5.5 | 5.5 | 2.9 | 2.2 | 2.3 | 82.9 | 0.15 | <0.01 | 0.47 | 6.39 |
| 7/10 | 0530 | 4.0 | 46.5 | 5.5 | 5.5 | 2.9 | 2.4 | 2.4 | 85.3 | 0.15 | <0.01 | 0.60 | 6.99 |

TABLE A-6. REGENERATION NO. 3:
DOUBLE REGENERATION PROCEDURE EMPLOYING 4% SODIUM HYDROXIDE, JULY 22, 1978

| Step | Flow rate (L/m) | Time (min) | Flow (L) | 55-gal Waste drum no. | Fluoride | | Arsenic | | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | mg/L | g/drum | mg/L | g/drum | |
| Backwash | 26.5 | 15 | 397 | | N.A. | N.A. | N.A. | N.A. | High turbidity |
| Upflow regeneration | 2.8 | 32 | 91 | 1 | 410 | 85.4 | 25.8 | 5.38 | |
| Upflow rinse | 3.8 | 31 | 117 | 1 | 410 | 85.4 | 25.8 | 5.38 | |
| Upflow rinse | 3.8 | 55 | 208 | 2 | 15 | 3.1 | 1.1 | 0.19 | |
| Upflow rinse | 3.8 | 55 | 208 | 3 | 6.9 | 1.4 | 0.67 | 0.13 | |
| Downflow regeneration | 2.8 | 32 | 91 | 4 | 41 | 8.6 | 7.2 | 1.49 | |
| Downflow neutralization | 5.7 | 20 | 117 | 4 | 41 | 8.6 | 7.2 | 1.49 | Rinse water pH - 2.0 |
| Downflow neutralization | 5.7 | 36 | 208 | 5 | 3.9 | 0.8 | 0.34 | 0.07 | Rinse water pH - 2.0 |
| Total | | | 1,437 | - | - | 99.3 | - | 7.26 | |

# APPENDIX B. FLUORIDE/ARSENIC REMOVAL PROJECT - PHASE II

TABLE B-1. TREATMENT RUN NO. 1 - COLUMN NO. 1

| Date | Δ Flow (kL) | Total flow (kL) | Adjusted raw water (pH) | Effluent (pH) | Raw water F (mg/L) | Effluent F (mg/L) | F removed in increment (g) | Total F removed (g) | Raw water As (mg/L) | Treated water As (mg/L) | As removed in increment (g) | As removed (g) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1/22 | 6.8 | 6.8 | 5.5 | 6.0 | 3.2 | <0.1 | 21.8 | 21.8 | 0.140 | <.005 | 1.0 | 1.0 |
| 1/23 | 8.3 | 15.1 | 5.4 | 5.5 | 3.2 | <0.1 | 25.1 | 47.5 | 0.140 | <.005 | 1.1 | 2.1 |
| 1/24 | 8.5 | 23.6 | 5.4 | 5.4 | 3.2 | 0.1 | 26.4 | 73.9 | 0.140 | <.005 | 1.2 | 3.3 |
| 1/25 | 7.7 | 31.3 | 5.3 | 5.3 | 3.2 | 0.4 | 22.7 | 96.6 | 0.140 | <.005 | 1.1 | 4.4 |
| 1/26 | 6.9 | 38.2 | 5.5 | 5.3 | 3.2 | 1.7 | 14.8 | 111.4 | 0.140 | <.005 | 1.0 | 5.4 |
| 1/27 | 6.7 | 44.9 | 5.4 | 5.4 | 3.2 | 1.4 | 11.1 | 122.5 | 0.140 | <.005 | 0.9 | 6.3 |
| 1/28 | 6.3 | 51.2 | 5.2 | 5.4 | 3.2 | 2.1 | 9.1 | 131.6 | 0.140 | <.005 | 0.9 | 7.2 |
| 1/29 | 5.9 | 57.1* | 4.8 | 5.2 | 3.2 | 3.0 | 3.8 | 135.4 | 0.140 | <.005 | 0.8 | 8.0 |
| 1/30 | 7.5 | 64.6 | 5.5 | 5.3 | 3.2 | 1.7 | 6.4 | 141.8 | 0.140 | <.005 | 1.1 | 9.1 |
| 1/31 | 2.8 | 67.4* | 3.1 | 5.0 | 3.2 | 6.9 | (3.1) | 138.7 | 0.140 | <.005 | 0.4 | 9.5 |
| 2/4 | 4.3 | 71.7 | 5.3 | 5.3 | 3.1 | 2.7 | 1.7 | 140.4 | 0.140 | <.005 | 0.5 | 10.0 |
| 2/5 | 7.4 | 79.1 | 5.3 | 5.3 | 3.1 | 1.8 | 6.3 | 146.7 | 0.140 | <.005 | 1.1 | 11.1 |
| 2/6 | 7.4 | 86.5 | 5.4 | 5.4 | 3.1 | 2.7 | 6.3 | 153.0 | 0.140 | <.005 | 1.0 | 12.1 |
| 2/7 | 7.4 | 93.9 | 5.2 | 5.2 | 3.1 | 2.9 | 2.2 | 155.2 | 0.140 | <.005 | 1.1 | 13.2 |
| 2.8 | 7.4 | 101.3 | 5.2 | 5.3 | 3.1 | 2.3 | 3.7 | 158.9 | 0.140 | <.005 | 1.0 | 14.2 |
| 2/9 | 7.5 | 108.8 | 5.5 | 5.4 | 3.1 | 2.4 | 5.6 | 164.5 | 0.140 | <.005 | 1.0 | 15.2 |
| 2/10 | 7.4 | 116.2 | 5.5 | 5.5 | 3.1 | 2.3 | 5.6 | 170.1 | 0.140 | .005 | 1.1 | 16.3 |
| 2/11 | 4.6 | 120.6 | 5.4 | 5.5 | 3.1 | 3.0 | 2.1 | 172.2 | 0.140 | .006 | 0.5 | 16.8 |

*Filters plugged, flow rate reduced, process upset.

TABLE B-2. TREATMENT RUN NO. 1 - COLUMN NO. 2

| Date | Δ Flow (L) | Total flow (L) | Influent (pH) | Effluent (pH) | Influent F (mg/L) | Treated water F (mg/L) | F removed increment (g) | Total F removed (g) |
|---|---|---|---|---|---|---|---|---|
| 1/22 | 6.3 | 6.8 | 6.0 | 7.6 | <0.1 | 0.3 | - | - |
| 1/23 | 8.3 | 15.1 | 5.5 | 5.9 | <0.1 | <0.1 | - | - |
| 1/24 | 8.5 | 23.6 | 5.4 | 5.5 | 0.1 | <0.1 | - | - |
| 1/25 | 7.7 | 31.3 | 5.3 | 5.4 | 0.4 | <0.1 | 1.9 | 1.9 |
| 1/26 | 6.9 | 38.2 | 5.3 | 5.4 | 1.7 | <0.1 | 7.2 | 9.1 |
| 1/27 | 6.7 | 44.9 | 5.4 | 5.4 | 1.4 | <0.1 | 10.7 | 19.8 |
| 1/28 | 6.3 | 51.2 | 5.4 | 5.4 | 2.1 | <0.1 | 11.0 | 30.8 |
| 1/29 | 5.9 | 57.1* | 5.2 | 5.4 | 3.0 | <0.1 | 15.0 | 45.8 |
| 1/30 | 7.5 | 64.6 | 5.3 | 5.4 | 1.7 | 0.2 | 16.5 | 62.3 |
| 1/31 | 2.8 | 67.4* | 5.0 | 5.4 | 6.9 | 0.6 | 10.9 | 73.2 |
| 2/4 | 4.3 | 71.7 | 5.3 | 5.4 | 2.7 | 0.8 | 17.6 | 90.8 |
| 2/5 | 7.4 | 79.1 | 5.3 | 5.4 | 1.8 | 1.0 | 10.0 | 100.8 |
| 2/6 | 7.4 | 86.5 | 5.4 | 5.4 | 2.7 | 0.9 | 9.6 | 110.4 |
| 2/7 | 7.4 | 93.9 | 5.2 | 5.4 | 2.9 | 1.2 | 13.0 | 123.4 |
| 2/8 | 7.4 | 101.3 | 5.3 | 5.4 | 2.3 | 1.2 | 10.4 | 133.8 |
| 2/9 | 7.5 | 108.8 | 5.4 | 5.4 | 2.4 | 1.6 | 7.1 | 140.9 |
| 2/10 | 7.4 | 116.2 | 5.5 | 5.4 | 2.3 | 1.8 | 4.8 | 145.7 |
| 2/11 | 7.6 | 120.6 | 5.5 | 5.4 | 3.0 | 2.4 | 4.2 | 149.9 |

*Filters plugged, flow rate reduced, process upset.

TABLE B-3. REGENERATION NO. 1:
DOUBLE REGENERATION PROCEDURE, MARCH 2, 1979

| Column No. | Step | NaOH (%) | Flow rate (L/min) | Time (min) | Flow (L) | 55-gal waste drum no. | Fluoride | | Arsenic | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | mg/L | Drum (g) | mg/L | Drum (g) |
| 1 | Backwash | N.A. | 26.5 | 15 | 397 | N.A. | N.A. | N.A. | N.A. | N.A. |
| 1 | Upflow regeneration | 4 | 2.8 | 32 | 91 | 1 | 727 | 151.5 | 41.1 | 8.6 |
| 1 | Upflow rinse | N.A. | 5.7 | 21 | 117 | 1 | 727 | 151.5 | 41.1 | 8.6 |
| 1 | Upflow rinse | N.A. | 5.7 | 37 | 208 | 2 | 17 | 3.5 | 2.5 | 0.5 |
| 1 | Downflow regeneration | 1 | 2.8 | 32 | 91 | 3 | 14 | 2.9 | 3.5 | 0.7 |
| 1 | Downflow neutralization | N.A. | 5.7 | 21 | 117 | 3 | 14 | 2.9 | 3.5 | 0.7 |
| Subtotal Column 1 | | - | - | - | 1,021 | - | - | 157.9 | - | 9.8 |
| 2 | Backwash | N.A. | 26.5 | 15 | 397 | N.A. | N.A. | N.A. | N.A. | N.A. |
| 2 | Upflow regeneration | 1 | 2.8 | 32 | 91 | 1 | 360 | 75.0 | N.A. | N.A. |
| 2 | Upflow rinse | N.A. | 5.7 | 21 | 117 | 1 | 360 | 75.0 | N.A. | N.A. |
| 2 | Upflow rinse | N.A. | 5.7 | 37 | 208 | 2 | 100 | 20.9 | N.A. | N.A. |
| 2 | Downflow regeneration | 1 | 2.8 | 32 | 91 | 3 | 26 | 5.4 | N.A. | N.A. |
| 2 | Downflow neutralization | N.A. | 5.7 | 21 | 117 | 3 | 26 | 5.4 | N.A. | N.A. |
| Subtotal Column 2 | | - | - | - | 1,021 | - | - | 101.3 | - | - |
| Total | | - | - | - | 2,042 | - | - | 259.2 | - | 9.8 |



TABLE B-4. TREATMENT RUN NO. 2 - COLUMN NO. 1

| Date | Δ Flow (kL) | Total flow (kL) | Adjusted raw water (pH) | Effluent (pH) | Raw water F (mg/L) | Effluent F (mg/L) | F removed in increment (g) | Total F removed (g) | Raw water As (mg/L) | Treated water As (mg/L) | As removed in increment (g) | As removed (g) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3/2 | 0.5 | 0.5 | 2.5 | 10.8 | 3.0 | 2.5 | - | - | 0.140 | <.005 | - | - |
| 3/3 | 5.7 | 6.2 | 4.0 | 5.6 | 3.0 | 0.2 | 9.4 | 9.4 | 0.140 | <.005 | 0.7 | 0.7 |
| 3/4 | 7.9 | 14.1 | 5.3 | 5.5 | 3.0 | 0.3 | 21.7 | 31.1 | 0.140 | <.005 | 1.1 | 1.8 |
| 3/5 | 7.8 | 21.9 | 5.3 | 5.3 | 3.0 | 0.1 | 21.8 | 52.8 | 0.140 | <.005 | 1.1 | 2.9 |
| 3/6 | 7.9 | 29.8 | 5.5 | 5.5 | 3.0 | 0.1 | 22.9 | 75.8 | 0.140 | <.005 | 1.1 | 4.0 |
| 3/7 | 6.0 | 35.8 | 5.3 | 5.3 | 3.0 | 0.7 | 15.6 | 91.4 | 0.140 | <.005 | 0.8 | 4.8 |
| 3/8 | 6.8 | 42.6 | 5.3 | 5.3 | 3.0 | 2.2 | 10.5 | 101.9 | 0.140 | <.005 | 1.0 | 5.8 |
| 3/9 | 6.9 | 49.5 | *7.2 | 6.5 | 3.0 | 6.5 | (3.5) | 98.4 | 0.140 | <.005 | 0.9 | 6.7 |
| 3/10 | 7.1 | 56.6 | 5.3 | 5.4 | 3.0 | 2.2 | (0.7) | 97.7 | 0.140 | .007 | 1.0 | 7.7 |
| 3/11 | 7.6 | 64.2 | 5.3 | 5.3 | 3.0 | 2.0 | 6.8 | 104.5 | 0.140 | .007 | 1.0 | 8.7 |
| 3/12 | 7.1 | 71.3 | 5.3 | 5.3 | 3.0 | 2.4 | 5.7 | 110.2 | 0.140 | .007 | 1.0 | 9.7 |
| 3/13 | 7.5 | 78.8 | 5.3 | 5.3 | 3.0 | 2.6 | 3.8 | 114.0 | 0.140 | .007 | 0.9 | 10.6 |
| 3/14 | 7.3 | 86.1 | 5.4 | 5.3 | 3.0 | 2.4 | 3.7 | 117.7 | 0.140 | .008 | 1.0 | 11.6 |
| 3/15 | 7.0 | 93.1 | 5.4 | 5.3 | 3.0 | 2.5 | 3.9 | 121.6 | 0.140 | .010 | 1.0 | 12.6 |
| 2/16 | 7.1 | 100.2 | 5.4 | 5.3 | 3.0 | 3.0 | 1.8 | 123.4 | 0.140 | .010 | 0.9 | 13.5 |

*Acid pump suction tubing loosened, acid feed stopped, process upset.

TABLE B-5. TREATMENT RUN NO. 2 - COLUMN NO. 2

| Date | Δ Flow (L) | Total Flow (L) | Influent (pH) | Effluent (pH) | Influent F (mg/L) | Treated water F (mg/L) | F removed increment (g) | Total F removed (g) |
|---|---|---|---|---|---|---|---|---|
| 3/2 | 0.5 | 0.5 | 10.8 | - | 2.5 | 1.1 | - | - |
| 3/3 | 5.7 | 6.2 | 5.6 | 8.8 | 0.2 | 0.1 | 4.3 | 4.3 |
| 3/4 | 7.9 | 14.1 | 5.5 | 5.6 | 0.3 | <0.1 | 1.6 | 5.9 |
| 3/5 | 7.8 | 21.9 | 5.3 | 5.4 | 0.1 | <0.1 | 1.6 | 7.5 |
| 3/6 | 7.9 | 29.8 | 5.5 | 5.4 | 0.1 | <0.1 | 0.8 | 8.3 |
| 3/7 | 6.0 | 35.8 | 5.3 | 5.4 | 0.7 | 0.1 | 1.8 | 10.1 |
| 3/8 | 6.8 | 42.6 | 5.3 | 5.3 | 2.2 | <0.1 | 9.5 | 19.6 |
| 3/9 | 6.9 | 49.5 | *6.5 | 6.3 | 6.5 | 0.1 | 24.5 | 44.1 |
| 3/10 | 7.1 | 56.6 | 5.4 | 5.7 | 2.2 | 0.5 | 22.0 | 66.1 |
| 3/11 | 7.6 | 64.2 | 5.3 | 5.4 | 2.0 | 1.1 | 9.9 | 76.0 |
| 3/12 | 7.1 | 71.3 | 5.3 | 5.4 | 2.4 | 1.3 | 7.1 | 83.1 |
| 3/13 | 7.5 | 78.8 | 5.3 | 5.4 | 2.6 | 1.8 | 7.1 | 90.2 |
| 3/14 | 7.3 | 86.1 | 5.3 | 5.3 | 2.4 | 2.1 | 4.0 | 94.2 |
| 3/15 | 7.0 | 93.1 | 5.3 | 5.3 | 2.5 | 2.1 | 2.5 | 96.7 |
| 3/16 | 7.1 | 100.2 | 5.3 | 5.3 | 3.0 | 2.5 | 3.2 | 99.9 |

*Acid pump suction tubing loosened, acid feed stopped, process upset.

TABLE B-6. REGENERATION NO. 2:
DOUBLE REGENERATION PROCEDURE, MARCH 25, 1979

| Column No. | Step | NaOH (%) | Flow rate (L/min) | Time (min) | Flow (L) | 55-gal waste drum no. | Fluoride | | Arsenic | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | mg/L | Drum (g) | mg/L | Drum (g) |
| 1 | Backwash | N.A. | 26.5 | 15 | 397 | N.A. | N.A. | N.A. | N.A. | N.A. |
| 1 | Upflow regeneration | 4 | 2.8 | 32 | 91 | 1 | 534 | 111.3 | 43.7 | 9.2 |
| 1 | Upflow rinse | N.A. | 5.7 | 21 | 117 | 1 | 534 | 111.3 | 43.7 | 9.2 |
| 1 | Upflow rinse | N.A. | 5.7 | 37 | 208 | 2 | 20 | 4.2 | 1.6 | 0.3 |
| 1 | Upflow rinse | N.A. | 5.7 | 37 | 208 | 3 | 6 | 1.2 | 0.5 | 0.1 |
| 1 | Downflow regeneration | 1 | 2.8 | 32 | 91 | 4 | 24 | 5.0 | 3.3 | 0.6 |
| 1 | Downflow neutralization | N.A. | 5.7 | 21 | 117 | 4 | 24 | 5.0 | 3.3 | 0.6 |
| Subtotal Column 1 | | - | - | - | 1,230 | - | - | 121.7 | - | 10.2 |
| 2 | Backwash | N.A. | 26.5 | 15 | 397 | N.A. | N.A. | N.A. | N.A. | N.A. |
| 2 | Upflow regeneration | 1 | 2.8 | 32 | 91 | 1 | 314 | 65.5 | N.A. | N.A. |
| 2 | Upflow rinse | N.A. | 5.7 | 21 | 117 | 1 | 314 | 65.5 | N.A. | N.A. |
| 2 | Upflow rinse | N.A. | 5.7 | 37 | 208 | 2 | 58 | 12.1 | N.A. | N.A. |
| 2 | Downflow regeneration | 1 | 2.8 | 32 | 91 | 3 | 50 | 10.4 | N.A. | N.A. |
| 2 | Downflow neutralization | N.A. | 5.7 | 21 | 117 | 3 | 50 | 10.4 | N.A. | N.A. |
| Subtotal Column 2 | | - | - | - | 1,021 | - | - | 88.0 | - | - |
| Total | | - | - | - | 2,251 | - | - | 209.7 | - | 10.2 |

TABLE B-7. TREATMENT RUN NO. 3 - COLUMN NO. 1

| Date | Δ Flow (kL) | Total flow (kL) | Adjusted raw water (pH) | Effluent (pH) | Raw water F (mg/L) | Effluent F (mg/L) | F removed in increment (g) | Total F removed (g) | Raw water As (mg/L) | Treated water As (mg/L) | As removed in increment (g) | As removed (g) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3/25 | 1.3 | 1.3 | 4.0 | 8.6 | 2.8 | 0.2 | 3.4 | 3.4 | 0.140 | - | - | - |
| 3/26 | 6.5 | 7.8 | 5.3 | 5.4 | 2.8 | <0.1 | 17.6 | 21.0 | 0.140 | <.005 | 1.0 | 1.0 |
| 3/27 | 7.3 | 15.1 | 5.3 | 5.3 | 2.8 | <0.1 | 19.7 | 40.7 | 0.140 | <.005 | 1.0 | 2.0 |
| 3/28 | 7.1 | 22.2 | 5.3 | 5.3 | 2.8 | <0.1 | 19.2 | 59.9 | 0.140 | <.005 | 1.0 | 3.0 |
| 3/29 | 7.6 | 29.8 | 5.3 | 5.3 | 2.8 | 0.6 | 19.0 | 78.9 | 0.140 | <.005 | 1.0 | 4.0 |
| 3/30 | 7.6 | 37.4 | 5.3 | 5.3 | 2.8 | 1.5 | 13.3 | 92.2 | 0.140 | <.005 | 1.1 | 5.1 |
| 3/31 | 7.2 | 44.6 | 5.3 | 5.3 | 2.8 | 1.9 | 7.9 | 100.1 | 0.140 | <.005 | 1.0 | 6.1 |
| 4/1 | 7.6 | 52.2 | 5.3 | 5.3 | 2.8 | 2.2 | 5.7 | 105.8 | 0.140 | <.005 | 1.1 | 7.2 |
| 4/2 | 7.2 | 59.4 | 5.2 | 5.3 | 2.8 | 2.3 | 4.0 | 109.8 | 0.140 | <.005 | 1.0 | 8.2 |
| 4/3 | 7.6 | 67.0 | 5.4 | 5.3 | 2.8 | 2.5 | 3.0 | 112.8 | 0.140 | .007 | 1.0 | 9.2 |
| 4/4 | 7.7 | 74.7 | 5.4 | 5.4 | 2.8 | 2.5 | 2.3 | 115.1 | 0.140 | .009 | 1.0 | 10.2 |
| 4/5 | 6.9 | 81.6 | 5.3 | 5.3 | 2.8 | 2.6 | 1.7 | 116.8 | 0.140 | .010 | 0.9 | 11.1 |
| 4/6 | 7.1 | 88.7 | 5.3 | 5.3 | 2.8 | 2.5 | 1.8 | 118.6 | 0.140 | .008 | 1.0 | 12.1 |
| 4/7 | 7.0 | 95.7 | 5.3 | 5.3 | 2.8 | 2.5 | 2.1 | 120.7 | 0.140 | .009 | 0.9 | 13.0 |
| 4/8 | 6.8 | 102.5 | 5.3 | 5.3 | 2.8 | 2.5 | 2.0 | 122.7 | 0.140 | .011 | 0.9 | 13.9 |

TABLE B-8. TREATMENT RUN NO. 3 - COLUMN NO. 2

| Date | Δ Flow (L) | Total Flow (L) | Influent (pH) | Effluent (pH) | Influent F (mg/L) | Treated water F (mg/L) | F removed increment (g) | Total F removed (g) |
|---|---|---|---|---|---|---|---|---|
| 3/25 | 1.3 | 1.3 | - | - | 0.2 | - | - | - |
| 3/26 | 6.5 | 7.8 | 5.5 | 5.5 | <0.1 | 0.1 | - | - |
| 3/27 | 7.3 | 15.1 | 5.3 | 5.3 | <0.1 | <0.1 | - | - |
| 3/28 | 7.1 | 22.2 | 5.3 | 5.3 | <0.1 | <0.1 | - | - |
| 3/29 | 7.6 | 29.8 | 5.3 | 5.3 | 0.6 | <0.1 | 2.3 | 2.3 |
| 3/30 | 7.6 | 37.4 | 5.3 | 5.3 | 1.5 | <0.1 | 8.0 | 10.3 |
| 3/31 | 7.2 | 44.6 | 5.3 | 5.3 | 1.9 | <0.1 | 12.2 | 22.5 |
| 4/1 | 7.6 | 52.2 | 5.3 | 5.3 | 2.2 | <0.1 | 11.8 | 34.3 |
| 4/2 | 7.2 | 59.4 | 5.3 | 5.3 | 2.3 | 0.5 | 15.5 | 49.8 |
| 4/3 | 7.6 | 67.0 | 5.3 | 5.3 | 2.5 | 1.0 | 12.5 | 62.3 |
| 4/4 | 7.6 | 74.7 | 5.4 | 5.4 | 2.5 | 1.0 | 11.4 | 73.7 |
| 4/5 | 6.9 | 81.6 | 5.3 | 5.4 | 2.6 | 1.8 | 7.9 | 81.6 |
| 4/6 | 7.1 | 88.7 | 5.3 | 5.3 | [illegible] | 1.7 | 5.7 | 87.3 |
| 4/7 | 7.0 | 95.7 | 5.3 | 5.3 | 2.5 | 1.8 | 5.3 | 92.6 |
| 4/8 | 6.8 | 102.5 | 5.3 | 5.3 | 2.5 | 2.3 | 3.1 | 95.7 |

TABLE B-9. REGENERATION NO. 3:
DOUBLE REGENERATION PROCEDURE, APRIL 15, 1979

| Column No. | Step | NaOH (%) | Flow rate (L/min) | Time (min) | Flow (L) | 55-gal waste drum no. | Fluoride | | Arsenic | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | mg/L | Drum (g) | mg/L | Drum (g) |
| 1 | Backwash | N.A. | 26.5 | 15 | 397 | N.A. | N.A. | N.A. | N.A. | N.A. |
| 1 | Upflow regeneration | 4 | 2.8 | 32 | 91 | 1 | 587 | 122.3 | 44.6 | 9.3 |
| 1 | Upflow rinse | N.A. | 5.7 | 21 | 117 | 1 | 587 | 122.3 | 44.6 | 9.3 |
| 1 | Upflow rinse | N.A. | 5.7 | 37 | 208 | 2 | 17 | 3.5 | 2.5 | 0.5 |
| 1 | Downflow regeneration | 1 | 2.8 | 32 | 91 | 3 | 18 | 3.8 | 3.9 | 0.8 |
| 1 | Downflow neutralization | N.A. | 5.7 | 21 | 117 | 3 | 18 | 3.8 | 3.9 | 0.8 |
| Subtotal Column 1 | | - | - | - | 1,021 | - | - | 129.6 | - | 10.6 |
| 2 | Backwash | N.A. | 26.5 | 15 | 397 | N.A. | N.A. | N.A. | N.A. | N.A. |
| 2 | Upflow regeneration | 1 | 2.8 | 32 | 91 | 1 | 248 | 51.7 | N.A. | N.A. |
| 2 | Upflow rinse | N.A. | 5.7 | 21 | 117 | 1 | 248 | 51.7 | N.A. | N.A. |
| 2 | Upflow rinse | N.A. | 5.7 | 37 | 208 | 2 | 138 | 28.8 | N.A. | N.A. |
| 2 | Downflow regeneration | 1 | 2.8 | 32 | 91 | 3 | 57 | 11.8 | N.A. | N.A. |
| 2 | Downflow neutralization | - | - | 21 | 117 | 3 | 57 | 11.8 | N.A. | N.A. |
| Subtotal Column 2 | | - | - | - | 1,021 | - | - | 92.3 | - | - |
| Total | | - | - | - | 2,042 | - | - | 225.9 | - | 10.6 |

## APPENDIX C. WATER ANALYSES

### TABLE C-1. ANALYSES OF WHY, ARIZONA, WELL WATER

| Characteristic | Amount* | Amount** |
|---|---|---|
| Total hardness as $CaCO_3$, mg/L | 108 | 105 |
| Calcium as $CaCO_3$, mg/L | 76 | 29 |
| Magnesium as $CaCO_3$, mg/L | 32 | 8 |
| Phenolphthalein alkalinity as $CaCO_3$, mg/L | 0 | 0 |
| Methyl orange alkalinity as $CaCO_3$, mg/L | 106 | 106 |
| Sulfate as $SO_4$, mg/L | 124 | 147 |
| Chloride as Cl, mg/L | 130 | 136 |
| Silica as $SiO_2$, mg/L | 45 | |
| Arsenic, mg/L | 0.17 | 0.10 |
| Fluoride, mg/L | 2.4 | 2.7 |
| Sodium, mg/L | | 145 |
| Iron, mg/L | | 0.1 |
| Copper, mg/L | | <0.05 |
| Manganese, mg/L | | <0.05 |
| Zinc, mg/L | | 0.2 |
| Nitrate, mg/L | | 3.8 |
| Silver, mg/L | | <0.01 |
| Chromium, mg/L | | 0.01 |
| Cadmium, mg/L | | <0.005 |
| Lead, mg/L | | <0.02 |
| Selenium, mg/L | | <0.005 |
| Mercury, mg/L | | <0.001 |
| Barium, mg/L | | <0.2 |
| pH | 7.81 | 7.5 |
| Specific conductance, µmhos | 950 | |

*Tests performed by Ray W. Hawksley Company, Richmond, California, February 28, 1978

**Tests performed by Arizona Testing Laboratories, Phoenix, Arizona, December 19, 1977